Developments in In-Situ Monitoring of Moisture in Pavement Structures by Time Domain Reflectometry (TDR)

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ABSTRACT

There is an unsatisfied need to be able to readily monitor, over a long period, the moisture contents of all elements of a pavement structure including the subgrade soils, granular subbases, bases and shoulders.

The technique of Time Domain Reflectometry (TDR), when applied to this problem, makes it possible to avoid all of the problems associated with calibration, simplifies the installation, in many instances, and ensures the long-term reliability of the system.

TDR equipment, developed primarily for use in locating breaks in transmission lines, has been in use for a long time. This reliable equipment is readily available on the market. The probes, which are used to sense the moisture contents, simply consist of a pair of stainless steel rods fitted with a matching transformer. The moisture content of the material around and between the rods influences the speed at which an electrical pulse travels through the probe. Although the nature of the material does not influence this speed, large stones (such as are used in granular bases) require a different calibration curve than is used for all other fine grained soils, sands, etc. The apparent dielectric constant Ka, calculated from the measurement, has been correlated with the volumetric water content of the soil (W_v). The moisture content by weight of soil is deduced from a knowledge of the bulk dry density of the material.

Test sites were instrumented in different parts of Ontario since October 1981, and monitored periodically. The results demonstrate the durability of the probes, and the stability of the readings necessary for long-term monitoring.

1/ INTRODUCTION

Conventional testing for moisture content of soil or granular pavement material involves disturbing the pavement structure to remove a sample of the material for testing in the laboratory. Thus it is impossible to reproduce the original testing conditions at any subsequent time, and long-term testing has to be judged on a statistical basis, i.e., at each time of testing there is a requirement for adequate numbers of samples.

To overcome this problem a number of techniques and appropriate equipment have been examined to measure certain properties of the soil in situ, correlating it with moisture content. The electrical measurement most commonly used in the past has been conductance (or its reciprocal, resistance). The sensors used absorb water from the surrounding soil [1]; the amount, salinity and temperature of the water determine the sensors' resistance. Problems of calibration, accuracy and the technique's sensitivity to other parameters e.g., temperature and pure water salinity, tend to outweigh its usefulness.

Another electrical measurement which is used is the capacitance from which the dielectric constant can be determined. A sensor developed by Selig and Wobschall [2] measures the frequency shift of an oscillator circuit, which is a function of K, the dielectric constant. The moisture content of the soil is correlated with the capacitance (C) or dielectric constant. Research with a large variety of diverse materials such as coal, glass, concrete, clays, silts, sands, wheat, and oats shows there is a single correlation curve of volumetric moisture content with K or C [3]. This is illustrated in Figure 1.

The use of Time Domain Reflectometry (TDR) for determining the volumetric water content (W_v) of earth materials, via measurements of the apparent dielectric constant (Ka), is described in Davis and Annan [4], and Topp, Davis, and Annan [5], Their results indicate that the relationship between Ka and W_v is not particularly sensitive to soil type, temperature, or soluble salt content, and that W_v could be determined within 2.5%. Patterson [6] demonstrated that the measurement error is about 1.5%. Smith and Patterson [7] have used the TDR technique to determine the volumetric unfrozen water content of

frozen soils. Smith and Patterson, through an OJT and CRP project with the Ontario Ministry of Transportation and Communications, examined the use of the TDR technique for in situ soil moisture measurement in highways [8].

This report briefly describes the equipment and techniques used for installing the probes and reading the instrument outputs. It also describes a number of probe installations and the results of monitoring over a three-year period.

2/ TIME DOMAIN REFLECTOMETRY (TDR)

Time Domain Reflectometry (TDR) is commonly used to locate faults in coaxial transmission lines. When a coaxial cable is connected to the TDR unit, fast rise-time pulses are launched down the cable and the incident (V_i) and reflected voltage (V_r) are sampled. The CRT of the unit displays the voltage reflection coefficient (ρ) (V_r/V_c) on the y axis and distance along the line on the x axis. The x and y axes can be converted to time and impedance axes, respectively. Figure 2 shows a CRT display for a 50 Ω coaxial cable with open and short circuit terminations. The travel time (tt) in the cable is a function of the dielectric constant (Ka) of the material separating the conductors, and the cable length, L.

$$Ka = \left[\frac{c \times tt}{L}\right]^2 \qquad (1)$$

where c is the free space pulse velocity (30 cm/nanosecond), tt is the travel time along the line (Nsec), when the TDR equipment cable dielectric is set to "air". L is the line length (cm).

Equation 1 is used to determine the apparent dielectric constant, Ka, of moist soils by measuring the travel time along a transmission line, of known length, embedded in the sample. The transmission lines (probe) used in these studies are balanced parallel rod lines (Figure 3). The probe consists of a coaxial cable which connects to the TDR, an RF pulse transformer and parallel stainless steel rods which are embedded in the soil and serve as the measurement 'cell'.

A stylized CRT trace for a probe embedded in a wet soil is shown in Figure 4. The A point, at the start of the parallel rod lines, is in the soil and the B point, which denotes the open circuit response, is at the end of the line. By measuring the travel time (tt) from A to B, Ka can be derived using Equation 1, as L can be measured.

The volumetric water content, W_v of the soil can be determined from the Ka - W_v table of Equation 2 for fine-grained mineral soils, or Equation 3 for gravel based soils (granular A, Figure 5).

$$Ka_v = 3.03 + 9.3\ W_v + 146\ W_v^2 - 76.7\ W_v^3$$
$$Ka = 3.91 + 30.1\ W_v + 198.8\ W_v^2 - 417.3\ W_v^3 \qquad (3)$$

The high pore water salinities, which can be found in highway materials during spring melt, were found to make moisture readings difficult unless a suitable probe design was chosen. Figure 6 shows TDR traces for saturated sand at various salinities for a 29.2 cm probe. On a dry mass basis, the open circuit of the probe, at 655 ppm Cl-, cannot be located on the TDR trace, hence, W_v cannot be determined. By reducing the probe length, the open circuit can be located; hence, W_v is determined (Figure 7).

3/ TDR EQIPMENT AND PROBES

The TDR equipment used in this project is a Tektronix 1502 TDR unit. This 1502 TDR is self-contained, weatherproofed and battery operated. The unit can be used to drive an x-y or y-t recorder to obtain a hard copy of the CRT display (Figure 8).

The stainless steel rods used for probes in the field installations were made in MTC workshops and will be described later. The circuit mounting boards were made in the Carleton University workshops. Assembly of the rods, circuit board, matching transformer and connecting cable, and encapsulation of the probe head in an appropriate epoxy resin, was carried out in the MTC research section. The probes used were one of three types:

Type L - 0.3 cm dia. rods, displaced head, 15 cm long parallel lines at 2.5 cm spacing.

Type M - 1.0 cm dia. rods, 12.5 cm long parallel lines at 5.0 cm spacing.

Type N - 1.0 cm dia. rods, 15.0 cm long parallel lines at 5.0 cm spacing.

3.1/ Type L

This probe is constructed with the head displaced from the parallel lines by a shielded twin-lead TV wire. Since the cost of the transformer is about $50 and one head can service many probes, this is the most economical probe to construct.

Because the twin-lead wire is electrically lossy, the signal attenuation is increased and therefore the end of the parallel lines (B point) are particularly hard to establish when the moisture and salt content are high.

3.2/ Type M

This probe is constructed with its head connected directly to the parallel lines which is then connected to the coaxial cable input line.

The head is later encapsuled in a casting resin. The shorter 12.5 cm line lengths were used in this type to see if the B point could be better identified when the moisture and salinity were high. It is used at Sites 4 and 5, Probe 1.

3.3/ Type N

The construction of this type is identical to Type M except the line length is 15.0 cm. It is used at all other locations.

Each probe is tested to ascertain the connecting cable's characteristic pattern of impedance and junctions with the matching transformer and with the head of the stainless steel rods. This pattern remains the same for the probe wherever it is installed. A copy of the probe signature is kept for future reference,
although an experienced operator can identify point A without this signature record (Figure 9). The distance between A and B is a measure of the travel time (tt) in nanoseconds. Knowing the length L of the stainless steel rods from the bottom of the probe head to the ends of the rods, the dielectric constant Ka is calculated from Equation 1. Having determined Ka, the value of volumetric moisture (W_v) content, is determined from the regression in Equations 2 or 3, or from tabulated solutions of these equations.

If the dry density of the material is known or measured by means of the sand cone or balloon methods, then the moisture content by weight (W) can be derived by dividing W_v by the dry density
($W = \frac{W_v}{\text{dry density}}$). The dry density need only be taken initial
ly, at the time of installation, as small changes in dry density do not greatly influence the derived values of moisture content, W.

The cost for one probe is as follows:

Threaded Stainless Steel Rods	$ 5.00	
Circuit Board	4.00	
Transformer	50.00	ANZAC TP-103
Cable 6 m	6.00	58 A/U or 58 C/U
BNC Connector	1.00	UG 88/U
Epoxy	2.50	Scotch cast Electrical Insulating Resin #4
Total	$ 68.50	

4/ FIELD INSTALLATIONS

A number of field probe installations have been in place at six locations in the province since 1980.

4.1/ Site 1 - Highway 401

The TDR probes were installed at this location in July 1980 and readings were recorded until April 1981. At this time the original probes were removed so shoulder drains and a partial paved shoulder could be placed as part of a contract to resurface this section of highway. Before the partial paved shoulders were placed, the TDR probes were reinstalled at the same location in June 1981 (Figure 10).

Before June 1981, the average percentage of moisture for the base was 9.6% (July 1980 - May 1981). After June 1981, the percentage of moisture had an average of 6.4% (June 1981 - April 1983). Similarly, the moisture in the subbase was reduced from 13.4% to 10.9%.

4.2/ Sites 2 and 3, Highway 402 Experimental Shoulder Drains

Site 2 - The pipe was placed in a trench and backfilled with clear stone and the shoulder recompacted.

Site 3 - The filter-wrapped plastic pipe was ploughed in and the shoulder was recompacted. All the TDR probes installed at these sites were type L.

The probes at Site 3 were placed adjacent to a T-junction outlet pipe (this is perhaps why the percentages of moisture at Site 3 were higher, as all the water in the pipes drained to this area).

On two occasions -- January 27, 1981 and February 23, 1982 -- there was a sharp increase in moisture. Table 3 is a list of maximum temperatures for a period prior to these increases. In both situations, the sharp increase followed a period of five to six days of maximum temperatures above freezing (Table 1).

4.3/ Site 4, Highway 402

This site has a full depth asphalt pavement (48 cm) placed on a silty sand subgrade. A severe frost heave developed in the spring of the first year. Shoulder drains were placed at the edge of pavement and the edge of the shoulder in 1980.

In the fall of 1981, a 30 cm pipe was placed approximately 1.05 m below the ditch line (Figure 11).

TDR probes were placed at the edge of the pavement at 52 and 100 cm.

The 30 cm pipe placed on the ditch line lowered the water table and stopped the flow of water from the cut. Its effect on the moisture under the pavement was delayed, but as shown in Figure 12, the percentage of moisture has decreased markedly and is now more uniform.

4.4/ Sites 5 and 6, Highway 402

Probes were installed at these locations at the same time as Site 4. Site 5 is in a fill area (1.5 m) and Site 6 is in a cut area (4 m). There are no shoulder drains or ditch drains in these areas. Probe 2 at Site 6 is not operating. As shown in the summary of these two locations (Table 5), the moisture content is very high here. Soft shoulder signs are placed along this section of the highway.

4.5/ Sites 7 and 8, Highway 60
Sites 9 and 10, Highway 17

TDR moisture probes were placed at these two locations to compare the moisture between gravel shoulders and surface treated or waterproofed shoulders. At sites 7 and 8, probes were also installed at the centre line of the road. The data from these locations is very limited and no conclusions can be made.

4.6/ Sites 11 and 12, Highway 3N

This location is an experimental concrete pavement. Site 11 has a full-depth concrete slab (30 cm) placed directly on the subgrade. Site 12 has 23 cm of concrete with an 8 cm bituminous base placed on the subgrade. Shoulder drains were ploughed in, as part of the original construction, prior to the placing of the gravelled shoulders. Partial paved shoulders are to be placed on completion of the contract. Both sites are placed at T-junction outlets. There is only limited data at these sites, for the period of November 82 - April 83.

4.7/ In Situ Monitoring

The probes at the six locations described above have been monitored at two-week intervals during late winter and springtime, and at monthly intervals during the remainder of the year.

Due to the breakdown of the TDR cable tester (twice in three years) or the inclement weather, this schedule could not always be kept.

Summaries of results at all locations are listed in Tables 3 to 8.

4.8/ New Developments

The probes which have been used in the work described above have all been installed horizontally, at the depths indicated (Table 2), through the vertical side of a hole dug in the shoulder next to the pavement edge. All connecting wires were buried in the shoulder and led up to a waterproof box mounted on a post at the edge of the shoulder.

Earlier, a probe with discontinuities along its length, installed vertically through the pavement surface, had been experimented with but did not prove to be successful. A different design of vertical probe has now been developed which promises to allow the measurement of a continuous moisture profile. This probe consists of a balanced parallel rod line mounted on a PVC tube (2.5 cm dia.). Slots are milled in the tube and 0.3 cm brass or stainless steel rods (parallel lines) are placed in the slots. The probe head is connected directly to the parallel

lines. Probes can vary in length up to 1 m. One access hole, vertical or horizontal, is drilled then the probe is placed in the hole and backfilled. The results of the testing and a method for analyzing the readings are now being studied at Carleton University.

Experiments to measure moisture content in other materials have also been initiated.

The Ministry is monitoring the effects of cathodic protection systems by measuring the corrosion current in reinforced concrete structures. Since corrosion currents are influenced by
the temperature and moisture content of the concrete, a way of measuring this moisture could be helpful.

TDR moisture probes (Type L) were placed in two fresh Portland cement concrete cylinders (10 cm by 20 cm). One cylinder had salt added to the concrete mix.

Figure 13 is a series of x-y plots from one of the cylinders (no salt).

1/ Oven dryed 24 hours, weight 3798 g.
2/ Soaked for 2 days, weight 3965 g.
3/ Air dried for 4 days, weight 3913 g.

This experiment will continue with the installation of TDR probes in a structure.

5/ CONCLUSIONS

- TDR technology is feasible for long-term in situ measurement of soil moisture content.

- The 'transmission line' probes are very stable sensors.

- The sensors are quite inexpensive; they have functioned for at least three years in the field and one expects many more good years from them.

- There are many situations where long-term moisture measurement is useful and necessary. At Highway 402 site, for example, after a large drainage pipe flowing half full had been installed, it took two years for the moisture content at the pavement edge to stabilize at a lower value.

- Use of sensored moisture has demonstrated that pavement edge drains do reduce moisture content at the subbase.

- The one problem with TDR sensors in the spring thaw, when soils are saturated and contain high salt content, is the difficulty experienced in identifying the B point and therefore the moisture content.

- The TDR monitoring equipment is available off-the-shelf equipment which is portable and relatively free from mainterance problems. However, care is essential for trouble-free use.

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Table 1

Moisture Temperature Readings, Hwy. 402

Date	Maximum Temperature	Moisture Content W	
		Site 2	Site 3
80 12 12		4.7	5.7
81 01 20	- 0.6		
21	- 2.5		
22	1.6		
23	1.5		
24	0.5		
25	4.9		
26	6.7		
27	1.5	10.7	12.1
28	- 1.6		
29	- 5.5		
30	- 7.5		
81 02 27		5.1	10.7
82 02 03		4.0	5.0
11	- 9.1		
12	- 6.2		
13	- 3.8		
14	2.0		
15	4.8		
16	0.6	7.1	8.2
17	- 0.7		
18	0.4		
19	0.8		
20	2.0		
21	1.0		
22	3.5		
23	1.4	18.2	18.2
24	- 4.2		
25	- 4.9		
26	- 1.3		
27	- 0.3		
28	- 2.7		
82 03 30		5.4	9.6

Table 2

Summary of Depth and Transverse Locations

Site No.	Probe 1		Probe 2		Probe 3		Transverse
	Depth	Layer	Depth	Layer	Depth	Layer	
	cm		cm		cm		
1	25	Base	40	Subbase	48	Subgrade	All at edge of pavement
1	35	Base	50	Subbase	58	Subgrade	After May 81, Probe 1&2 edge of Pavement Probe 3 shoulder
2	17	Base	40	Subbase	47	Subgrade	All at edge of pavement
3	17	Base	32	Subbase	38	Subgrade	All at edge of pavement
4	52	Subgrade	100	Subgrade			Edge of pavement
5	55	Subgrade	100	Subgrade			Edge of pavement
6	50	Subgrade					Edge of pavement
7	12	Base	50	Subgrade	3	Base	Probe 1&2, edge of pavement Probe 3, centreline of pavement
8	12	Base	50	Subgrade	3	Base	Probe 1&2, edge of pavement Probe 3, centreline of pavement
9	30	Base	60	Subgrade			Edge of pavement
10	30	Base	60	Subgrade			Edge of pavement
11	39	Subgrade					Edge of pavement
12	39	Subgrade					Edge of pavement

TDR MOISTURE PROBES HIGHWAY 401 SHANLEY ROAD

SITE 1

AUGUST 1980 TO APRIL 1981 GRAVEL SHOULDERS-NO DRAINS
APRIL 1981 TO PRESENT PARTIAL PAVED SHOULDER -SHOULDER DRAINS

PROBE 1 23 CM GRANULAR A MATERIAL
PROBE 2 38 CM GRANULAR C MATERIAL
PROBE 3 AUG 80-APR 81 46 CM CLAY MATERIAL EDGE OF PAVEMENT
JUNE 81-APR 83 36 CM CLAY MATERIAL EDGE OF SHOULDER

DATE	VOLUMETRIC MOISTURE CONTENT SITE 1			MOISTURE CONTENT SITE 1		
	1	2	3	1	2	3
26AUG80	.	18.0	23.4	.	8.2	12.9
16SEP80	12.4	18.0	.	5.6	8.2	.
25NOV80	26.0	34.0	27.5	12.7	15.5	15.2
17DEC80	.	21.2	17.9	.	9.6	9.9
01JAN81	.	.	.	.	.	.
28JAN81	.	29.1	.	.	13.2	.
24FEB81	26.6	31.7	31.7	12.2	14.4	17.5
03MAR81	19.5	.	38.4	8.9	.	21.2
16MAR81	24.7	.	37.1	11.2	.	20.5
06APR81	21.2	.	34.4	9.6	.	19.0
15APR81	18.0	52.7	38.4	8.2	24.0	21.2
22APR81	18.0	31.7	38.4	8.2	14.4	21.2
23JUN81	11.4	18.0	31.7	5.2	8.2	17.5
01JUL81	.	.	.	.	.	.
14JUL81	18.1	20.6	21.9	8.2	9.4	12.1
23SEP81	15.9	26.4	36.1	7.2	12.0	19.9
01JAN82	.	.	.	.	.	.
20APR82	14.0	20.9	32.1	6.4	9.5	17.7
12MAY82	13.4	21.0	32.3	6.1	9.5	17.8
23JUN82	13.4	26.1	36.3	6.1	11.9	20.1
01JUL82	.	.	.	.	.	.
05OCT82	11.3	25.3	26.4	5.1	11.5	15.7
01NOV82	11.9	25.2	23.7	5.4	11.5	13.1
07DEC82	14.2	29.8	32.1	6.5	13.5	17.7
01JAN83	.	.	.	.	.	.
24JAN83	12.5	16.6	11.6	5.7	7.5	6.4
28FEB83	17.4	30.0	24.1	7.9	13.6	13.3
28APR83	14.2	29.0	30.6	6.5	13.2	16.9

Table 3

TDR MOISTURE PROBES HIGHWAY 402

EXPERIMENTAL SHOULDER DRAINS

SITE 2 PIPE IN TRENCH
PROBE 1 17 CM GRANULAR MATERIAL
PROBE 2 40 CM CLAY MATERIAL
PROBE 3 47 CM CLAY MATERIAL

SITE 3 PIPE PLOUGHED IN
PROBE 1 17 CM GRANULAR MATERIAL
PROBE 2 32 CM CLAY MATERIAL
PROBE 3 38 CM CLAY MATERIAL

VOLUMETRIC WATER CONTENT

DATE	SITE 2			SITE 3		
	1	2	3	1	2	3
01DEC80	10.3	37.3	36.1	20.7	37.2	60.0
15DEC80	10.3	42.9	37.3	12.5	47.7	60.0
01JAN81	.	.	.	.	.	.
27JAN81	23.5	52.0	52.6	26.7	52.6	42.9
27FEB81	11.3	40.7	40.7	23.5	52.0	60.0
10MAR81	13.5	35.1	52.0	23.5	46.5	60.0
06APR81	13.5	35.1	52.0	26.3	42.9	55.1
27MAY81	11.4	40.7	52.0	26.3	47.7	60.0
16JUN81	11.4	45.4	55.1	23.5	46.9	60.0
01JUL81	.	.	.	.	.	.
12AUG81	15.7	45.3	52.6	23.5	47.7	59.9
15SEP81	13.5	40.7	40.7	22.0	46.5	52.6
09OCT81	13.6	36.2	38.4	21.9	46.5	52.6
30OCT81	15.5	38.4	41.9	20.7	38.4	50.1
27NOV81	11.4	33.9	38.4	21.9	40.7	52.6
09DEC81	11.4	36.1	38.4	18.0	40.7	52.6
01JAN82	.	.	.	.	.	.
06JAN82	12.0	37.1	39.1	22.9	37.1	49.6
20JAN82	8.7	26.3	21.4	12.9	27.9	25.1
03FEB82	8.8	25.1	18.9	10.9	24.2	22.5
16FEB82	15.6	24.0	19.7	18.0	26.3	27.3
23FEB82	40.0	26.8	21.4	40.0	26.0	24.5
30MAR82	11.8	33.8	39.0	21.2	45.4	60.0
21APR82	10.6	38.2	39.8	18.2	55.8	60.0
03MAY82	9.1	21.1	38.4	15.8	43.9	54.0
11MAY82	10.4	33.7	45.2	16.7	47.7	60.0
25MAY82	13.4	36.9	47.1	24.4	60.0	60.0
10JUN82	8.4	45.6	48.8	20.0	45.5	59.9
29JUN82	9.6	43.6	53.9	21.0	47.7	60.0
01JUL82	.	.	.	.	.	.
27JUL82	9.1	42.3	40.7	20.6	45.9	49.2
30SEP82	11.0	44.3	43.5	19.6	44.1	56.1
22NOV82	10.6	42.3	38.2	20.0	43.9	49.7
01JAN83	.	.	.	.	.	.
10JAN83	9.0	32.0	35.0	21.0	42.0	47.0
15FEB83	10.3	24.3	22.0	18.8	24.2	32.6
09MAR83	11.8	33.3	34.8	20.6	45.1	50.1
19APR83	9.8	40.7	35.9	20.0	44.7	56.7

MOISTURE CONTENT

	SITE 2			SITE 3		
	1	2	3	1	2	3
01DEC80	4.7	20.6	19.9	9.4	20.6	33.1
15DEC80	4.7	23.7	20.6	5.7	26.4	33.1
01JAN81	.	.	.	.	.	.
27JAN81	10.7	26.7	18.1	12.1	18.1	23.7
27FEB81	5.1	22.5	22.5	10.7	25.7	33.1
10MAR81	6.1	19.4	26.7	10.7	25.7	33.1
06APR81	6.1	19.4	26.7	12.0	23.7	30.4
27MAY81	5.2	22.5	28.7	12.0	26.4	33.1
16JUN81	5.2	25.1	30.4	10.7	27.0	33.1
01JUL81	.	.	.	.	.	.
12AUG81	7.1	25.0	29.1	10.7	26.4	33.1
15SEP81	6.1	22.5	22.5	10.0	25.7	29.1
09OCT81	6.2	20.0	21.2	10.0	25.7	29.1
30OCT81	7.0	21.2	23.1	9.4	21.2	27.7
27NOV81	5.2	18.7	21.2	10.0	22.5	29.1
09DEC81	5.2	19.9	21.2	8.2	22.5	29.1
01JAN82	.	.	.	.	.	.
06JAN82	5.5	20.5	21.6	10.4	20.5	27.4
20JAN82	4.0	14.5	11.6	5.9	15.4	13.9
03FEB82	4.0	13.9	10.4	5.0	13.4	12.4
16FEB82	7.1	15.3	10.9	8.2	14.5	15.1
23FEB82	18.2	14.8	11.6	18.2	14.4	13.5
30MAR82	5.4	18.7	21.5	9.6	25.1	33.1
21APR82	4.8	21.1	22.0	8.3	30.8	33.1
03MAY82	4.1	11.7	21.2	7.2	24.3	29.8
11MAY82	4.7	18.6	25.0	7.6	26.4	33.1
25MAY82	8.1	20.4	26.0	11.1	33.1	33.1
10JUN82	3.8	25.2	27.0	9.1	25.1	33.1
29JUN82	4.4	24.1	29.8	9.5	26.4	33.1
01JUL82	.	.	.	.	.	.
27JUL82	4.1	23.4	22.5	9.4	25.4	27.2
30SEP82	5.0	24.5	24.0	8.9	24.4	31.0
22NOV82	4.8	23.4	21.1	9.1	24.3	27.5
01JAN83	.	.	.	.	.	.
10JAN83	4.1	17.7	19.3	9.5	23.2	26.0
15FEB83	4.7	13.4	12.2	8.5	13.4	16.0
09MAR83	5.4	18.4	19.2	9.4	24.9	27.7
19APR83	4.5	22.5	19.8	9.1	24.7	31.3

Table 4

TDR MOISTURE PROBES HIGHWAY 402 EAST BOUND LANES

SITE 4 CUT AREA (SEVERE FROST HEAVE)
PROBE 1 50 CM CLAY MATERIAL
PROBE 2 100CM CLAY MATERIAL

SITE 5 FILL AREA
PROBE 1 50 CM CLAY MATERIAL
PROBE 2 100CM CLAY MATERIAL

SITE 6 CUT AREA
PROBE 1 50 CM CLAY MATERIAL

	VOLUMETRIC WATER CONTENT					MOISTURE CONTENT				
DATE	SITE 4		SITE 5		SITE 6	SITE 4		SITE 5		SITE 6
	1	2	1	2	1	1	2	1	2	1
09DEC81	17.9	14.7	22.7	47.6	41.1	10.2	8.4	11.8	24.6	21.3
01JAN82	.	.	.	.	.	.	.	.	.	.
06JAN82	33.0	17.2	35.4	33.6	39.4	18.9	9.6	18.6	17.5	20.4
20JAN82	33.0	16.4	19.7	41.1	9.2	18.4	9.4	10.2	21.3	4.8
03FEB82	38.6	14.1	20.9	34.4	13.2	22.1	8.1	10.8	17.8	6.8
16FEB82	35.6	12.8	22.5	27.3	25.1	20.5	7.3	11.7	14.1	13.0
23FEB82	26.6	20.4	24.0	39.0	43.9	16.3	11.7	12.4	20.2	22.7
30MAR82	21.2	27.1	25.7	60.0	60.0	12.1	15.5	13.3	31.1	31.1
21APR82	12.8	23.7	26.4	60.0	43.1	7.3	13.5	13.9	31.1	22.3
03MAY82	12.8	16.1	26.6	60.0	43.1	7.3	9.2	13.9	31.1	22.3
11MAY82	12.3	15.2	26.6	60.0	42.8	7.1	8.7	14.8	31.1	22.2
25MAY82	8.8	12.5	25.1	60.0	44.0	5.0	7.1	18.2	31.1	22.8
10JUN82	11.7	14.4	26.8	60.0	44.8	6.7	8.2	13.9	31.1	23.1
29JUN82	12.5	14.3	30.4	56.6	46.9	7.1	8.2	15.8	29.3	24.3
01JUL82	.	.	.	.	.	.	.	.	.	.
27JUL82	12.6	13.4	31.0	60.0	51.8	7.2	7.7	16.1	31.1	26.8
30SEP82	8.4	12.6	30.1	60.0	46.7	4.8	7.2	15.6	31.1	24.2
22NOV82	11.7	9.0	26.6	60.0	40.6	6.7	5.1	14.8	31.1	21.0
01JAN83	.	.	.	.	.	.	.	.	.	.
10JAN83	11.6	15.0	31.0	60.0	39.5	6.6	8.6	16.1	31.1	20.5
15FEB83	13.3	15.0	19.7	34.8	35.1	7.6	8.6	10.2	18.0	18.2
09MAR83	19.2	19.7	32.7	60.0	41.9	11.0	11.3	16.9	31.1	21.7
19APR83	16.6	22.2	35.0	60.0	42.3	10.6	12.7	18.1	31.1	21.9

Table 5

TDR MOISTURE PROBES HIGHWAY 60 ROSEBANK - DOUGLAS

SITE 7 SURFACE TREATED SHOULDER
PROBE 1 12 CM GRANULAR MATERIAL
PROBE 2 50 CM SANDY MATERIAL
PROBE 3 17 CM GRANULAR MATERIAL (CENTRE LINE)

SITE 8 GRAVEL SHOULDER
PROBE 1 12 CM GRANULAR MATERIAL
PROBE 2 50 CM SANDY MATERIAL
PROBE 3 17 CM GRANULAR MATERIAL (CENTRE LINE)

VOLUMETRIC WATER CONTENT

	SITE 7			SITE 8		
	1	2	3	1	2	3
03JUN82	16.7	29.9	15.8	10.4	24.5	31.0
01JUL82	•	•	•	•	•	•
05OCT82	12.0	21.0	4.0	9.0	20.0	22.0
02NOV82	12.8	21.3	9.7	10.6	16.8	19.0
04NOV82	10.5	21.3	9.7	10.6	20.8	22.6
06DEC82	15.1	26.0	9.1	12.7	31.3	21.8
01JAN83	•	•	•	•	•	•
25JAN83	7.7	16.3	7.7	10.3	12.8	18.0
02MAR83	11.0	14.2	6.9	14.0	10.0	19.5
27APR83	12.7	26.0	12.7	9.8	22.2	30.0

MOISTURE CONTENT

	SITE 7			SITE 8		
	1	2	3	1	2	3
03JUN82	7.6	10.6	7.2	4.7	13.6	14.1
01JUL82	•	•	•	•	•	•
05OCT82	5.5	11.7	4.1	4.1	11.1	10.0
02NOV82	5.8	11.6	4.4	4.6	9.3	8.6
04NOV82	4.8	11.8	4.4	4.6	14.9	10.4
06DEC82	6.9	14.4	4.1	5.6	17.4	9.9
01JAN83	•	•	•	•	•	•
25JAN83	3.5	9.1	3.5	4.7	7.1	6.2
02MAR83	5.0	7.9	4.0	6.4	5.6	8.9
27APR83	5.6	14.4	5.6	4.5	12.3	13.6

Table 6

TDR MOISTURE PROBES HIGHWAY 17 PEMBROKE BYPASS

SITE 9 SURFACE TREATED SHOULDER
PROBE 1 30 CM GRANULAR MATERIAL
PROBE 2 60 CM CLAY MATERIAL

SITE 10 GRAVEL SHOULDER
PROBE 1 30 CM GRANULAR MATERIAL
PROBE 2 60 CM CLAY MATERIAL

DATE	VOLUMETRIC WATER CONTENT				MOISTURE CONTENT			
	SITE 9		SITE 10		SITE 9		SITE 10	
	1	2	1	2	1	2	1	2
05NOV82	9.1	37.5	0.1	41.5	4.1	20.8	0.0	23.1
06DEC82	12.6	39.9	10.5	42.3	5.7	22.2	7.5	23.5
01JAN83	.	.	.	.	.	.	.	.
24JAN83	3.1	11.7	6.0	15.6	1.4	6.5	2.7	8.6
02MAR83	11.6	12.6	13.2	15.6	5.4	7.0	6.0	8.8
27APR83	17.8	43.2	17.3	54.9	8.1	24.0	7.9	30.5

Table 7

TDR MOISTURE PROBES HIGHWAY 3N RUTHVEN

EXPERIMENTAL CONCRETE SECTION

SITE 11 FULL DEPTH CONCRETE SECTION
PROBE 1 39 CM SANDY CLAY

SITE 12 BITUMINOUS BASE SECTION
PROBE 1 39 CM SANDY CLAY

DATE	VOLUMETRIC WATER CONTENT		MOISTURE CONTENT	
	SITE 11	SITE 12	SITE 11	SITE 12
	1	1	1	1
24NOV82	38.4	38.4	21.3	21.3
01JAN83	.	.	.	.
10JAN83	31.0	39.5	17.2	21.9
14FEB83	14.3	22.7	7.9	12.6
09MAR83	32.5	40.3	18.1	22.4
20APR83	31.7	41.3	17.6	22.9

Table 8

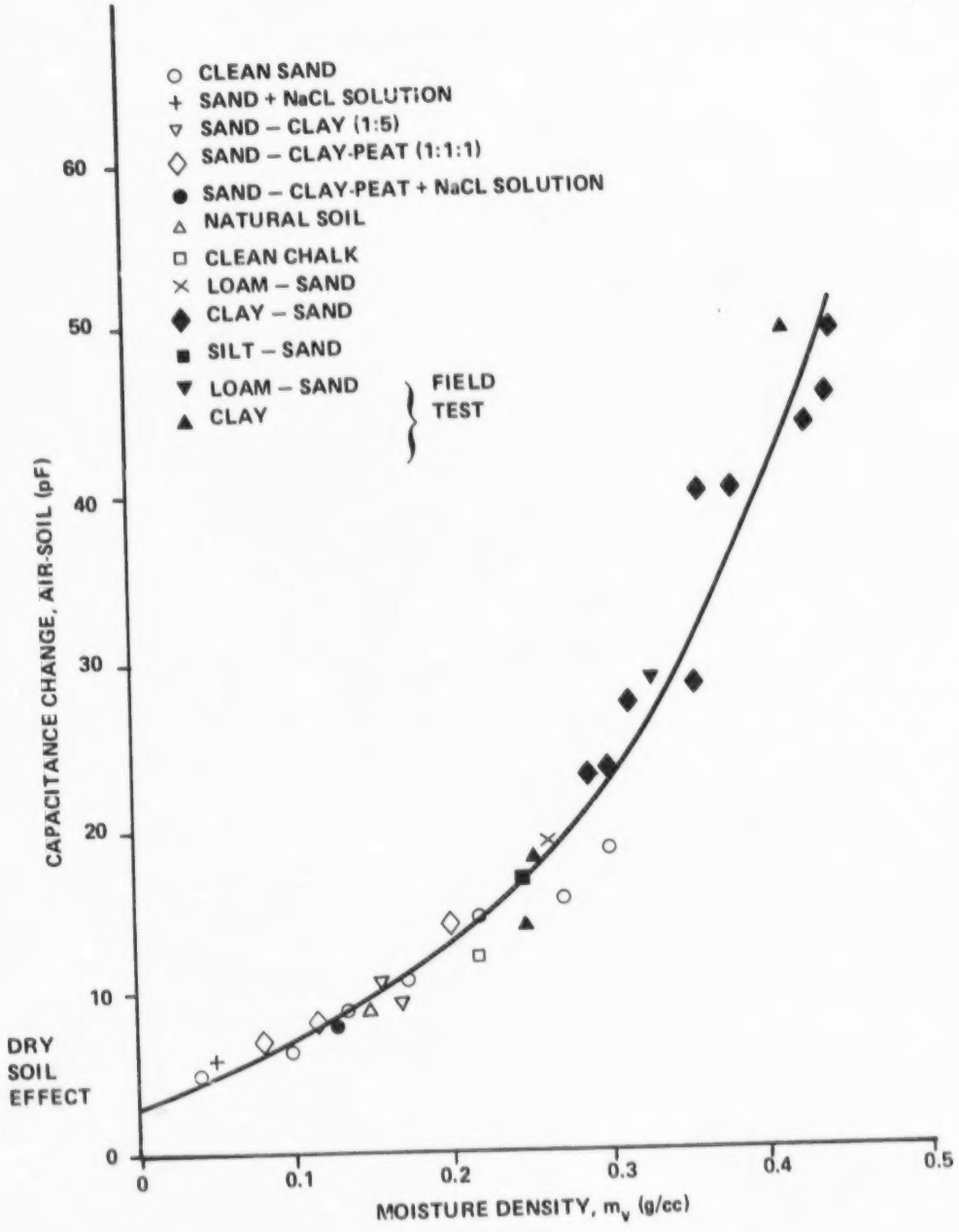
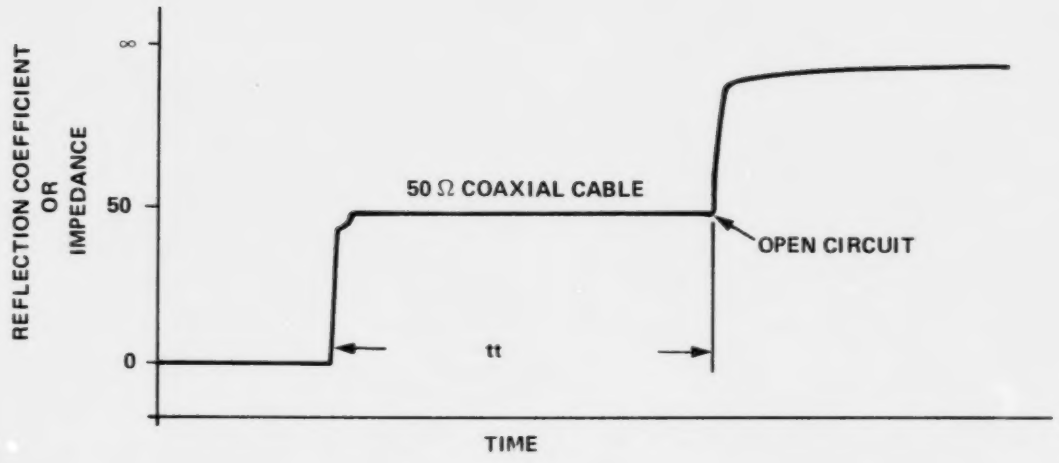
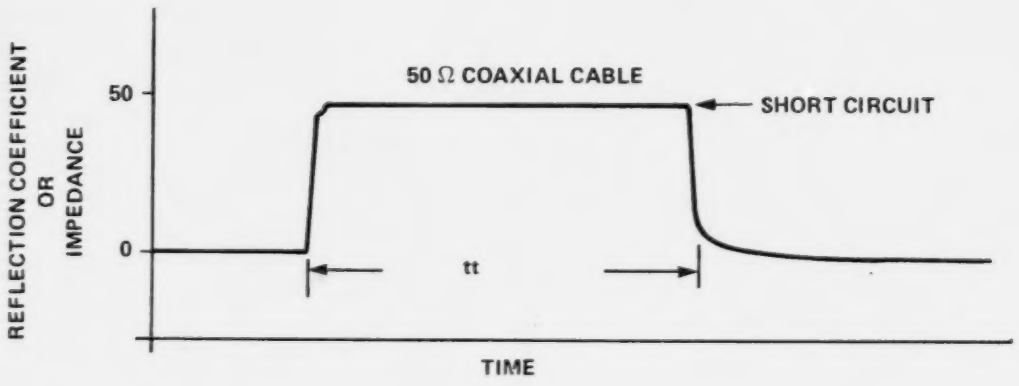


Figure 1/ Relationship Between Capacitance and Moisture Density for a Variety of Soils (3).



(a) Open-Circuited Cable



(b) Short Circuited Cable

Figure 2/ Typical Trace for a Coaxial Cable

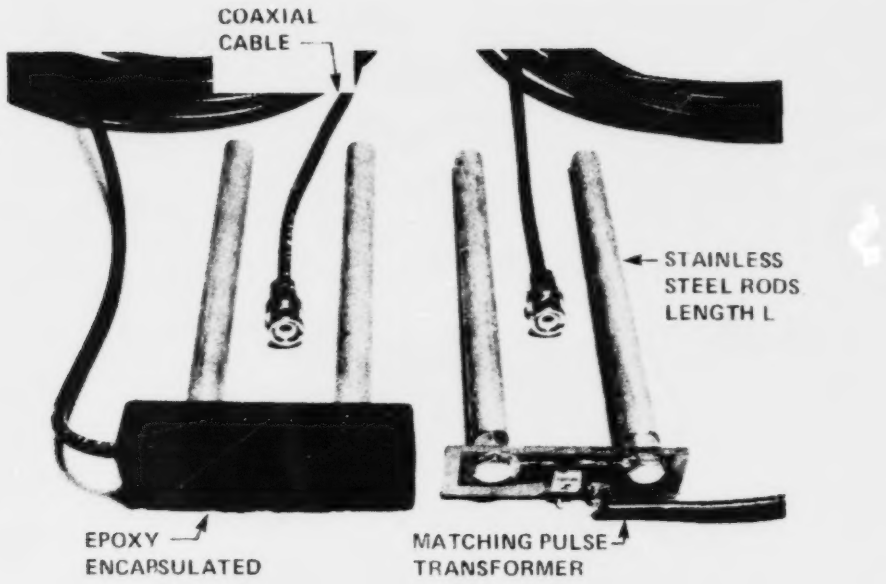


Figure 3/ TDR Probes

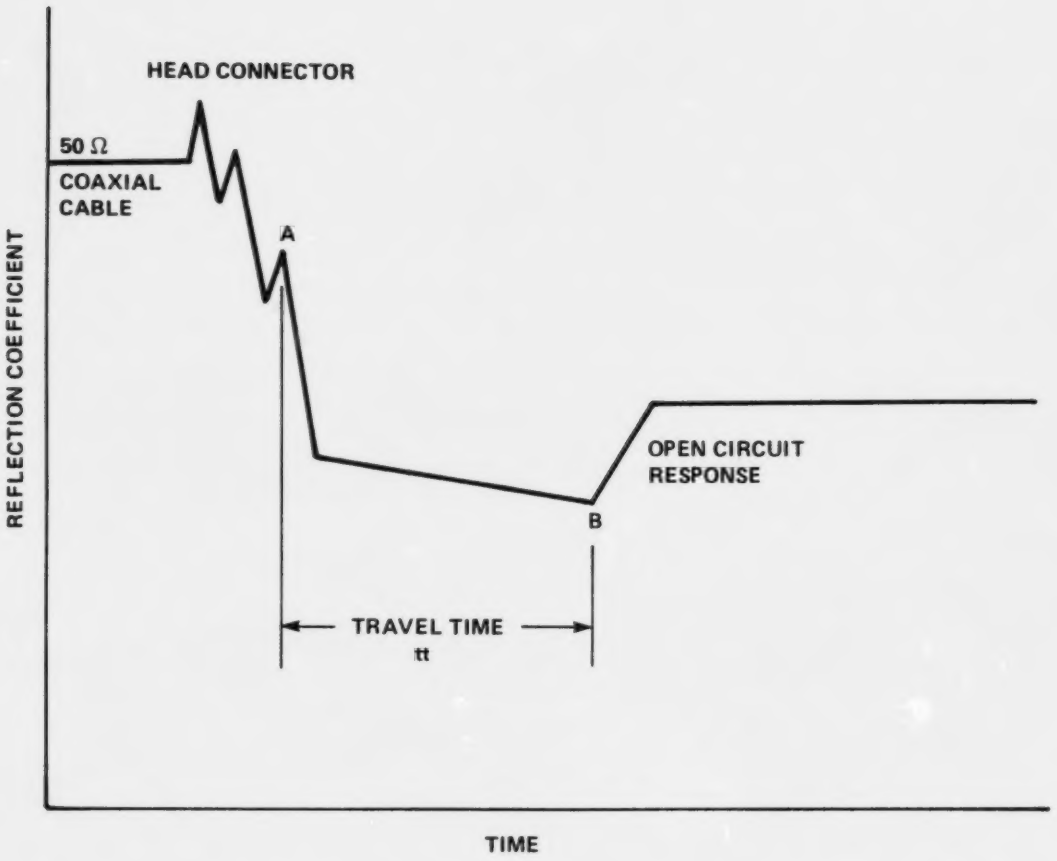


Figure 4/ Stylized TDR Trace of a Parallel Line In a Wet Soil

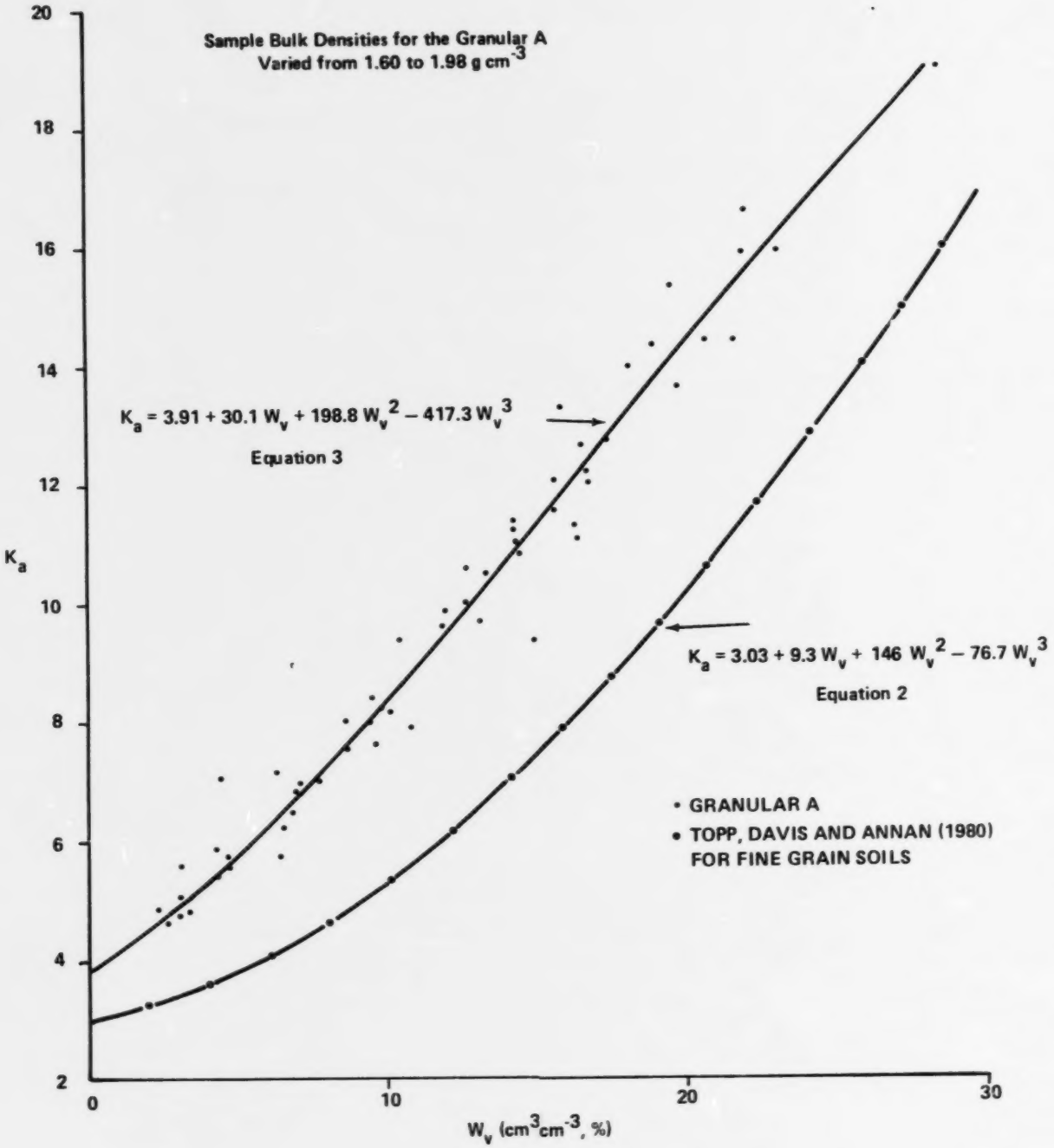
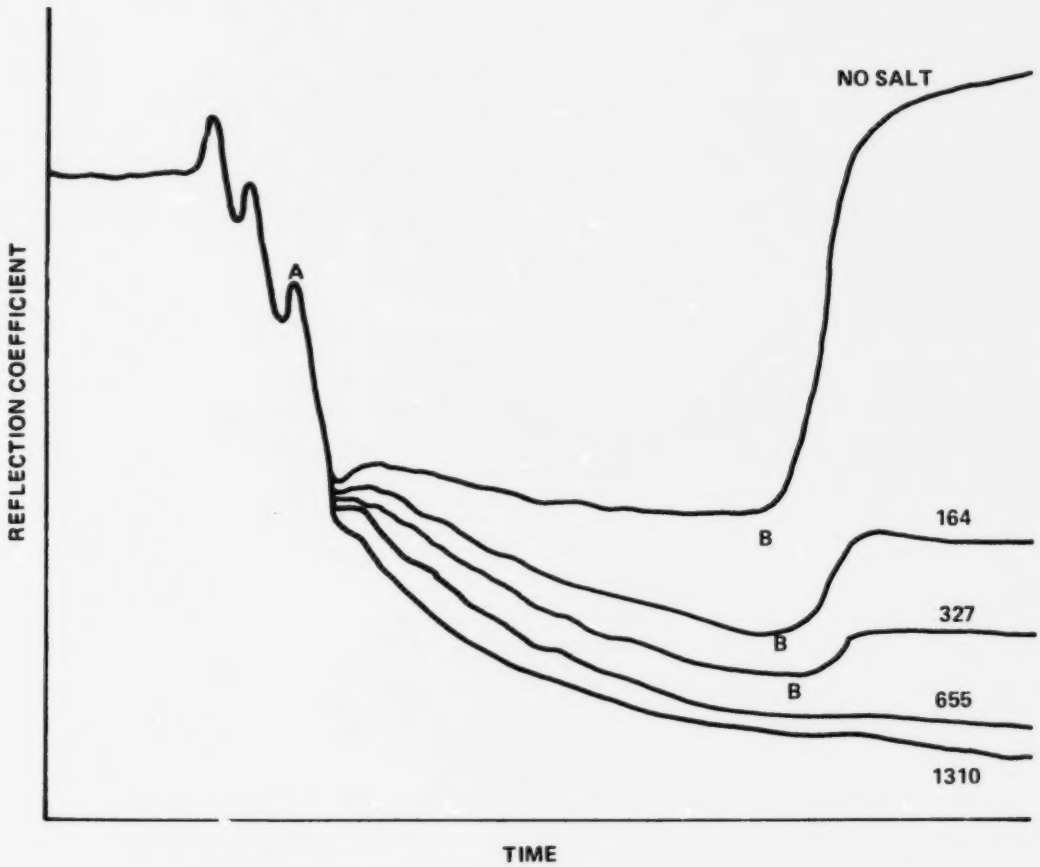


Figure 5/ $K_a - W_v$ for Granular A and Fine Grain Soils



SOURCE: Patterson and Lewis, 1981.

Figure 6/ TDR Traces for Various Salinities (PPM Cl^-) for a 29.2 cm Probe

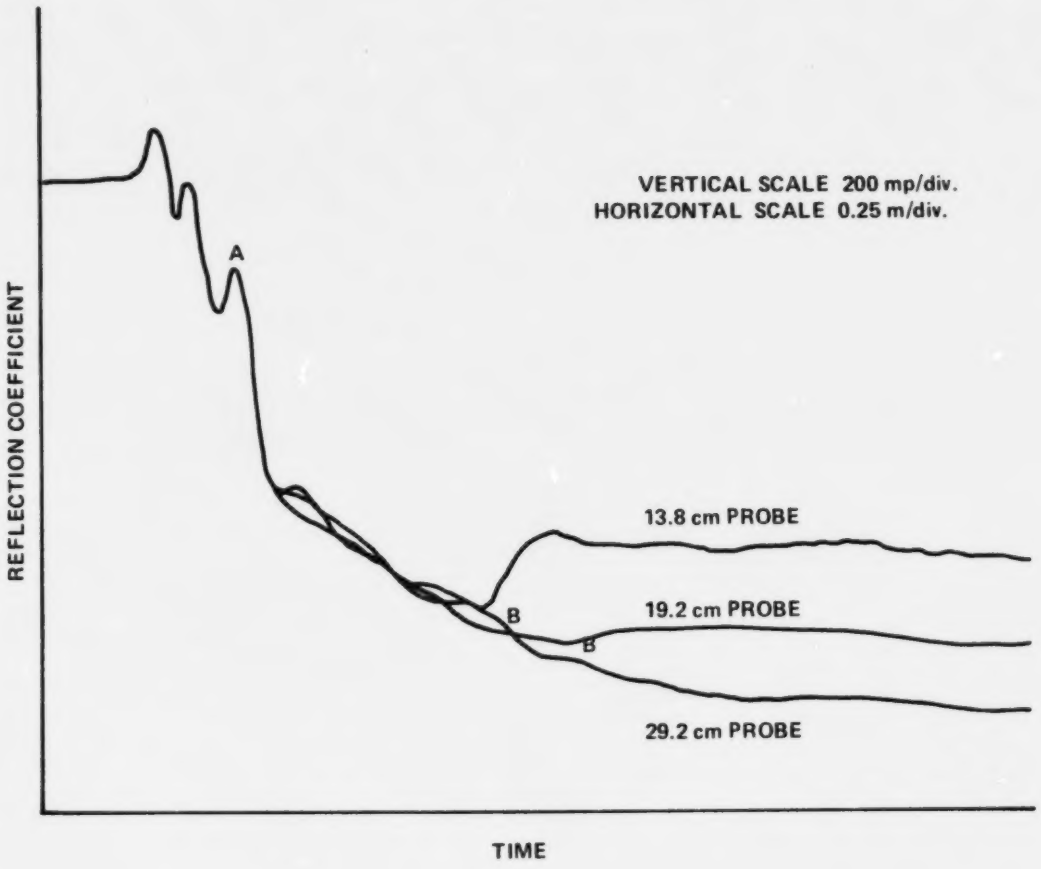


Figure 7/ TDR Traces for Three Probes Lengths (Salinity 655 PPM Cl^-)

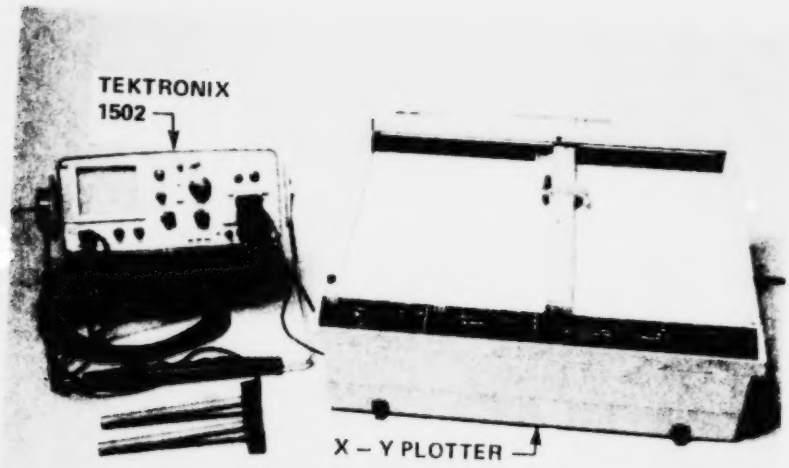
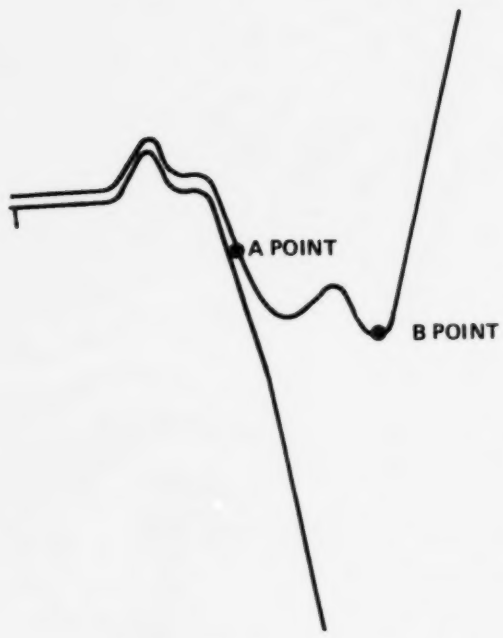
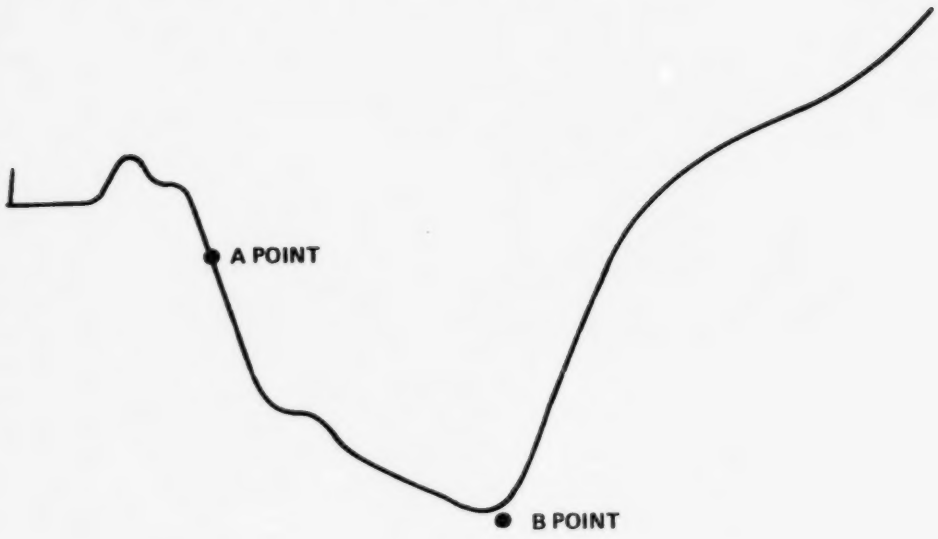


Figure 8/ TDR 1502 and X – Y Plotter



PROBE SIGNATURE



X – Y PLOT AFTER INSTALLATION

Figure 9/ Identifying A Point

SITE 1 – HIGHWAY 401

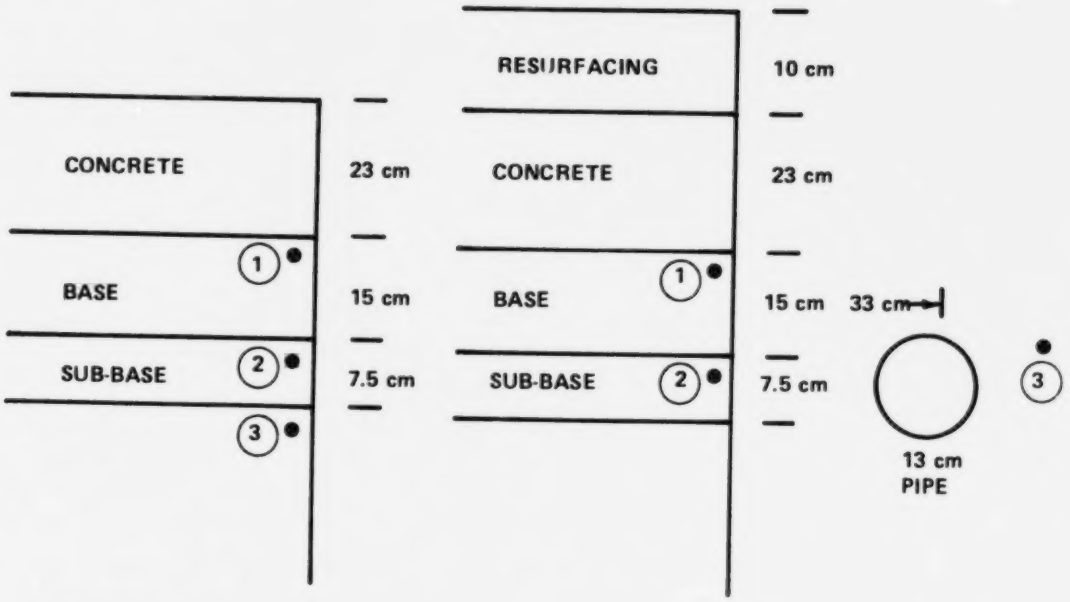
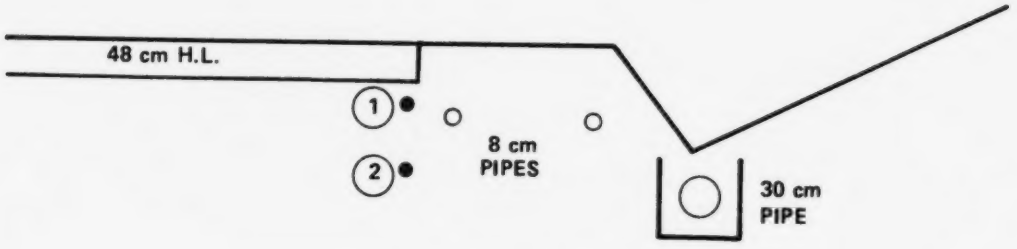


Figure 10/ Site 1 – Highway 401 Probe Locations

SITE 4 – HIGHWAY 402



SEVERE FROST HEAVE

Figure 11/ Site 4 – Highway 402 Probe Locations

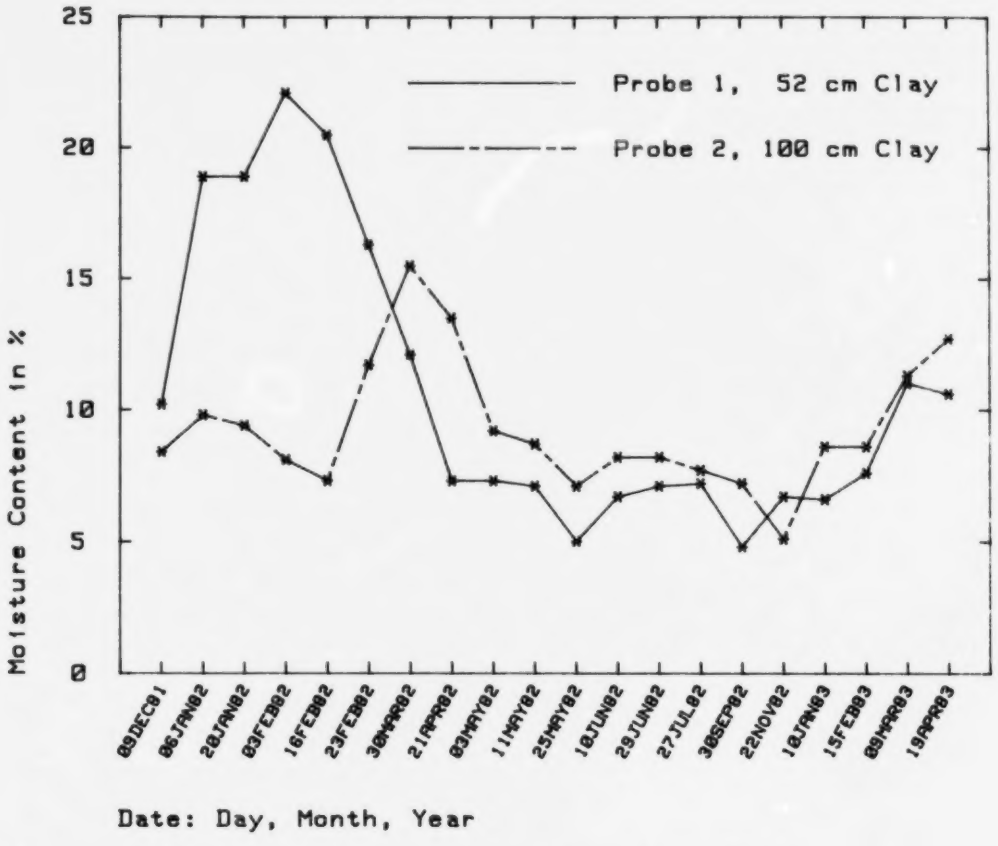


Figure 12/ TDR Moisture Probes: Hwy. 402 East Bound Lanes, Site 4.

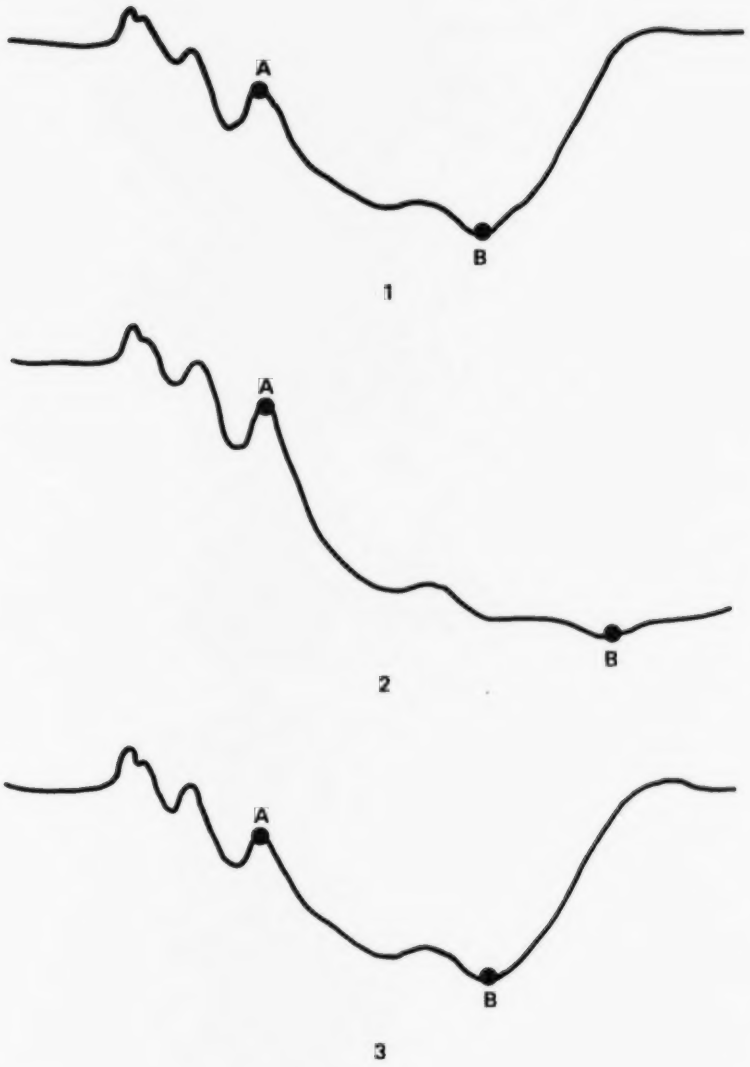


Figure 13/ X – Y Plot TDR Probe In Concrete Cylinders